Conventional Hydroelectricity and the Future of Energy: Linking National Inventory of Dams and Energy Information Administration Data to Facilitate Analysis of Hydroelectricity

Emily Grubert[1*]
[1]School of Civil and Environmental Engineering, Georgia Institute of Technology; 790 Atlantic Drive, Atlanta, GA 30332, USA; gruberte@gatech.edu; 404.894.3055
[*]Corresponding author: gruberte@gatech.edu

Abstract

Within the energy community, conventional dam and reservoir-based hydroelectricity is often viewed as a low-cost, immediately available zero-carbon resource that could facilitate more intermittent renewable electricity integration, seasonal storage, and other grid benefits. Conventional hydroelectricity systems, however, are potentially unique among power plants in that energy provisioning is not the only priority for their fuel, stored water. This paper presents a record linkage between electricity- and dam management-oriented datasets to facilitate attention to the fundamental challenge of altering operational regimes for systems that have other uses.

Keywords: hydroelectricity, energy, water, renewable energy, multicriteria, constraint

1. Introduction

The electricity system is changing. Two of the most salient issues expected for the future electricity system are a need for zero-carbon resources in the face of a changing climate and anticipated growth in electricity demand (Levi et al., 2019). Zero-carbon resource use is associated with further changes, particularly in the form of new fuels and new power plant characteristics. A transition from thermal power plants using fossil fuels to zero-carbon resources entails reliance on highly diverse fuel cycles, including fossil fuel plant analogs burning biomass or using geothermally or solar heated fluids; turbine-based systems using fluids other than steam, like wind and hydroelectric facilities; and the semiconductor-based systems of solar photovoltaic generation. In addition to these fuel cycle changes, the nature of matching supply and demand changes with the inclusion of large amounts of intermittently available nondispatchable electricity from facilities like wind and solar generating stations, whether via use of demand response, electricity storage, or other methods (Lovins, 2017). Similarly, management regimes – particularly related to ancillary services – will likely change in response to increased participation by noninertial electricity providers (Brown et al., 2018).

As with the need for zero-carbon resources, electricity demand growth is multiple issues. Such demand growth takes fundamentally different forms depending on the nature of existing infrastructure. In areas that already meet electricity demand with good reliability, as in many parts of the United States (US), the major conversation focuses on adapting and adding to existing infrastructure to accommodate electrification of uses that have historically relied on non-electric carbon based fuels, such as natural gas for heating or industrial purposes or oil for transportation (Avendano and Rauss, 2019; Boßmann and Staffell, 2015; Philibert, 2019). This electricity demand growth is not primarily associated with satisfaction of additional demand for energy services, as it represents fuel switching rather than fulfilling an unmet need for energy. In much of the world, particularly areas with limited existing electricity infrastructure, electricity demand growth expectations are associated with expectations of additional energy service provision (Bazilian et al., 2012; Palit and Bandyopadhyay, 2016). These regions might also be expected to electrify systems currently relying on other fuels, further increasing growth expectations. Although existing infrastructure will need to be closely managed to avoid outages and other issues in both cases, and although even areas with mature grid infrastructure will likely require further investment, areas fulfilling additional energy service demands will likely see substantial opportunities and challenges associated with grid buildout (Nerini et al., 2016; Silva Herran and Nakata, 2012).

In light of these anticipated changes to electricity systems, substantial effort has been devoted to modeling potential future electricity systems (Chang et al., 2013; Cochran et al., 2014; Denholm and Hand, 2011; Pina et al., 2013), particularly focused on three Cs: carbon, capacity, and cost. Electricity models often focus particularly on the nature of electricity supply, defining generation facility capacity (e.g., in gigawatts, GW) by fuel type, in part because of the impact of capacity on costs, particularly for systems that do not pay for fuel (e.g., many renewable energy systems). For systems that do not rely on chemical energy-based fuels and thus produce little to no pollution at the margin while operating, capacity is also often a driver of environmental impacts because more impacts are embodied in the infrastructure than are associated with marginal production (Pehl et al., 2017). Whether such capacity can fulfill demand is often determined using capacity factors at a variety of spatiotemporal scales, which are measures of how much a given power generation facility can run. With varying degrees of sophistication, models also can account for the different extent of dispatchability associated with different types of generation facilities. That is, some facilities can rapidly ramp production up or down to meet grid needs, e.g., when many people turn on kettles during television commercial breaks, causing a demand spike (Bunn and Seigal, 1983) or when another generator trips offline, causing a supply collapse (Yamashita et al., 2009).

Conventional hydroelectricity—typically associated with dam and reservoir systems, but more generally associated with systems that divert water flow for power generation and often have the ability to impound water—is of special interest for potential future decarbonized, larger grids due to its unusual characteristics. One potentially obvious characteristic is that large amounts of conventional hydroelectricity already exist, which is unusual for generation assets that do not produce combustion emissions like carbon dioxide. As of 2018, conventional hydroelectricity accounts for 39% of US and 63% of global renewable energy consumption (BP, 2019). On mature grids, there is little expectation that more conventional hydroelectric systems will be built (Berga, 2016; Marriott et al., 2010), though some dams that currently do not have electricity generation capacity could be retrofitted for production (Hadjerioua et al., 2012). Despite this limited expectation for capacity growth, however, existing infrastructure is expected to remain in use for the foreseeable future due to the unusually long lifetime of dam-based systems relative to other power plants (EIA, 2019a; Grubert, 2019). In addition to the basic advantage of existence, hydroelectricity has unusual operational characteristics that make it valuable to the electricity grid when it can be operated for grid needs (Karier and Fazio, 2017). These include pre-conversion fuel storage (in the form of elevated water), black start capability, and highly responsive dispatchability.

Conventional hydroelectricity facilities are possibly unique among power plants in that energy provisioning is often not the only driver of their operations (François et al., 2014; US Army Corps of Engineers, 2019). That is, hydroelectricity assets are often integrated with a broader system of multipurpose infrastructure with critical additional priorities. Unlike a natural gas-fired power plant that exists solely to produce electricity and possibly steam or heat as an energy co-product, a dam might exist to impound water for municipal, agricultural, industrial, or recreational use; to facilitate navigation; to prevent major damages from floods; and a host of other purposes. Electricity generation is often the major or only revenue-generating activity for a given dam, but it is often not the primary priority for water management. The energy resource for hydroelectricity is potential or kinetic energy in water, which means that water must be moved downstream for power generation. Unlike essentially any other kind of power generator, hydroelectricity facilities emit a still-useful, scarce, carefully managed resource. Thus, the timing and location of passing water through dams for power generation has major implications for other water uses. Similarly, the material impacts of releasing water—that is, unleashing a mass-bearing flow in a particular channel at a particular time—means that downstream conditions need to be very carefully managed with respect to power generation. Ramping electricity production up and down can create flash floods, scour river channels, raise or lower lake levels by people's homes, and generally create undesirable outcomes related to the location and timing of water flows.

Conventional hydroelectricity generation assets are persistent infrastructure with capabilities that are highly valuable to electricity grid management, and which could become even more valuable as decarbonization and demand growth advance—subject to likely requirements for adjusted operational patterns. The restrictions on these assets that stem from their status as components of multipurpose infrastructure with highly diverse, societally critical and sometimes higher priority non-electricity mandates, however, is often not described or completely accounted for in energy-oriented models (Ibanez et al., 2014). Further, because of the fundamentally different types of uses and users of dam and reservoir systems, the data that can help inform a more complete representation of constraints on hydroelectricity operations are often incompatible with electricity-related data commonly used by the energy community.

This brief paper makes two contributions intended to facilitate better representations of conventional hydroelectricity in energy models and analysis. First, it presents a record linkage between Energy Information Administration (EIA) and National Inventory of Dams (NID) data for facilities accounting for an estimated 99% of US hydroelectricity generation (the full resource is published as an accompanying Excel File, Supplementary Data File 1—SDF1) (EIA, 2019a, 2019b; US Army Corps of Engineers, 2019). This record linkage associates unique identifiers for hydroelectricity facilities between the EIA and NID datasets, in addition to summarizing some basic data from each database. This paper presents some descriptive regionalized statistics about US hydroelectricity producing dams related to their stated NID primary purpose, for illustration of the types of analyses this record linkage enables. Second, this paper describes some of the particular policy and licensing procedures associated with US dams in order to contextualize some of the limitations on hydroelectricity production that might not be evident when electricity is the only analytical target.

2. Characterizing Conventional Hydroelectricity in the United States

Some characteristics of conventional dam and reservoir-based hydroelectricity systems are likely to be more valuable to future, larger, decarbonized electricity systems than they are now. Hydroelectricity facilities are (to first order, though see e.g., Demarty and Bastien, 2011) producers of zero-carbon electricity that have the ability to store energy (in the form of elevated water in a reservoir) and respond extremely quickly to the need for additional resources (due to their very high technical ramp rates, e.g., Holttinen et al., 2013), both unusual characteristics for generation assets that are advantageous for facilitating integration of intermittent generation resources. Many hydroelectricity facilities are very large, which means that dam-and-reservoir systems often have the technical capacity to replace electricity storage needs at instantaneous to seasonal scales. That is, hydroelectricity facilities could potentially alleviate the need for long-duration battery storage due to their ability to store water at scale.

As the grid faces disruptive changes, most notably with respect to the relationship between electricity supply and electricity demand and which system is asked to respond to the other, conventional hydroelectricity could be tasked with shifts in operational goals. Electricity models might account for technical limitations at hydroelectricity facilities without fully accounting for nonenergy constraints, like irrigation storage, navigation releases, or mandatory spill for ecological reaons (Zhou et al., 2018). Understanding the physical and policy constraints associated with highly regulated multipurpose infrastructure as it pertains to the electricity system will be important for accurately modeling the potential for hydroelectric contributions to the future grid. Enabling closer analysis of the relationships among hydroelectricity and other priorities for US dam-and-reservoir-based hydroelectricity facilities by identifying and linking data, with the goal of facilitating improved modeling of hydroelectricity participation in future electricity systems, is a major goal of this piece.

2.1 EIA and NID Record Linkage: Background and Methods

Large amounts of data about dam and reservoir systems are gathered and maintained, potentially due both to the critical infrastructure nature of these systems and to the fact that many are federally owned (FERC, 2013). From an energy systems perspective, however, such data are not necessarily linked in ways that enable a holistic understanding of hydroelectricity constraints. For example, the main electricity databases managed by EIA (Energy Information Administration) use different unique identifiers than the National Inventory of Dams (NID), the major dam-related database managed by the United States Army Corps of Engineers (USACE). This records gap means that associating power production with other dam characteristics can be fairly difficult. The issue of incompatible identifiers is exacerbated by the fact that other potential ways to match records from EIA data and the NID are imperfect due to the nature of the infrastructure in question. Hydroelectricity is often generated at facilities comprised of multiple large, integrated infrastructural components, which might be miles apart and all of which might have different, and sometimes multiple, names. For example: an investigator looking for information about the infrastructure system including California's Gianelli Power Plant, also called San Luis, would encounter the O'Neill and San Luis Dams (also called the B.F. Sisk Dam), associated with the O'Neill Forebay and San Luis Reservoirs. Grand Coulee Dam is associated with four separate powerhouses (Left, Right, Third, and Pump-Generating), each containing multiple generators. Its primary "reservoir," Franklin D. Roosevelt Lake, is essentially 150 miles of the Columbia River and is also called the Columbia Reservoir or Empire Lake. These types of issues mean that matching records based on infrastructure names or even GPS coordinates is challenging and often produces incorrect results. Further, some place names are common to multiple facilities.

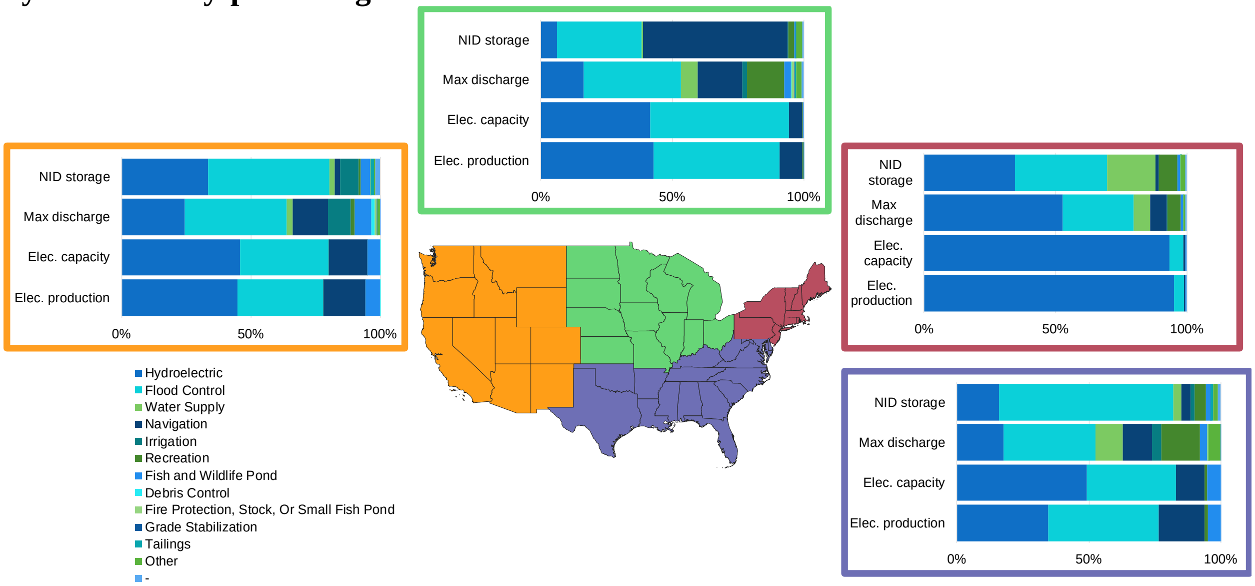
Supplementary Data File 1 (SDF1) links NID and EIA data for dams accounting for 99% of US hydroelectricity generation and 89% of US hydroelectricity capacity in 2017. Record linkage proceeded as follows. First, a coarse match based on longitude and latitude of EIA and NID records was applied, as described in Grubert, 2016, Supplementary Text Section 1.3. For that application, the primary goal was to determine the amount of electricity associated with dams in a general region, so mismatches at the dam level were an acceptable tradeoff of using this location-based match. For this work, however, the goal is to match dams correctly with associated hydroelectricity infrastructure. EIA and NID records were thus examined at the individual facility level for facilities producing either negative electricity (in the case of pumped storage hydro) or 50,000 MWh of electricity or more in 2017, based on EIA 923 records (EIA, 2019b). For facilities where the location-based match yielded a link between EIA and NID records, if the facility name was consistent across the two sources, it was presumed to be a correct match. If not, an Internet search was performed until either a match or an explanation for the lack of a match was identified. These searches frequently leveraged Google Maps satellite imagery. In the unusual cases where a match could not be identified, one common reason (clarified with satellite imagery) is that electricity might be produced without a dam. Given that the location-based matching technique often returned many-to-one matches, duplicate matches were explicitly searched and removed for facilities producing 25,000 MWh or more as of 2017. Ultimately, 291 million MWh of 294 million MWh of hydroelectricity generation was accounted for in the record linkage process, with facilities that were not individually checked (i.e., those producing <50,000 MWh in 2017) accounting for 12 million MWh (4%) and an upper bound on duplicate records (i.e., from records showing <25,000 MWh from a facility) of 7 million MWh (2%). The linkage includes over 1,000 unique facilities. See SDF1 for more validation details. Although some mismatches are likely still present in the data due to, e.g., error during the manual process, multiple facilities with the same name, and errors for dams producing <50,000 MWh, the dataset is relatively well vetted and is likely to be correct for most major facilities.

2.2 How Does Record Linkage Help? Electricity Generation and NID Primary Purpose

Linking records for hydroelectricity production with data about associated dams can facilitate a number of analyses potentially useful for understanding the context of hydroelectricity and its non-energy constraints. This paper presents one descriptive analysis that contextualizes hydroelectricity with respect to the NID's characterization of dams' primary purposes. Assessing dam primary purposes is a crude indicator of priority for two major reasons. First, it does not capture the balance among multiple purposes associated with a given facility. For example, a dam that has two equal purposes will still have a single stated primary purpose. Second, primary purpose as characterized by the NID is basically a reflection of why a given dam was built, not an accurate characterization of operational priorities. One particularly stark example of this is Grand Coulee Dam, the US' largest power plant by capacity, at about 7 gigawatts (EIA, 2019b): NID does not list hydroelectricity as a purpose at all (US Army Corps of Engineers, 2019), but the Northwest Power and Conservation Council notes that hydroelectricity generation accounts for about 80% of the dam's authorized purposes from a modern water management perspective (Northwest Power and Conservation Council, 2019). Despite the incompleteness of the characterization of dams given by their NID-listed primary purpose, understanding what kinds of dams are powered and how this varies across the US can help inform energy analysts' understanding of the context of these dams. For example, dams built for hydroelectricity likely have different ability to respond to grid needs than dams built for navigation, where river flow rates are likely important, or for irrigation, where the seasonality of water releases are likely important for the dams' primary users.

Figure 1 uses data from the record linkages provided in SDF1 to characterize US hydroelectricity-producing dams by region and primary purpose.

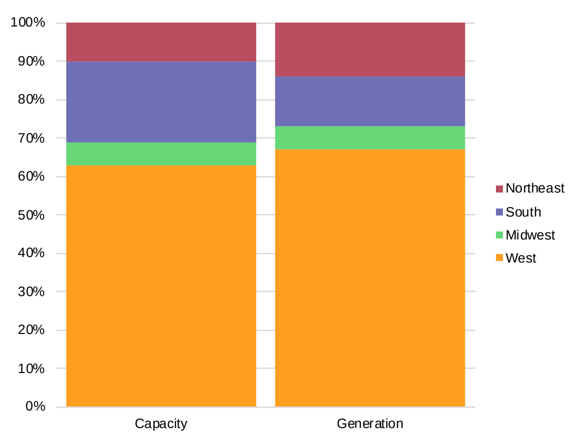
Figure 1. Regional distribution of dam and reservoir characteristics for US hydroelectricity-producing dams



Caption: Bar charts show the percentage of reservoir storage, maximum discharge capacity, electricity capacity, and electricity production for hydroelectricity-producing facilities in four major regions of the United States by the associated dams' NID-stated primary purpose.

Figure 2 shows each region's share of US hydroelectricity generation and capacity. Notably, the majority of US hydroelectricity is produced in the American West, with about 50% of the country's hydroelectricity produced in the Pacific Northwest.

Figure 2. 2017 US Hydroelectricity Capacity and Generation by Region



Caption: Most US hydroelectricity is generated in the West. A higher generation to capacity ratio indicates a higher capacity factor.

One takeaway from this investigation of dam purposes as they relate to electricity production is that regional variability is substantial. For example, hydroelectricity in the Northeast is primarily produced from dams with primary purpose = hydroelectricity, while hydroelectricity in other regions is often produced at dams with primary purpose = flood control or navigation (Figure 1). As Figure 2 shows, Northeastern dams also have higher capacity factors – that is, they produce more electricity per unit of capacity – which might be related to their greater degree of dedication to hydroelectricity production. SDF1 includes capacity factor data by region and dam primary purpose. Figure 1 also shows that dam characteristics like electricity production are not linearly correlated with reservoir characteristics, such as storage volume and discharge capacity. These distinctions have implications not only for operational constraints, but also for environmental impacts like water intensity and others (Grubert, 2016; Zhang et al., 2019).

3. Hydroelectricity Governance and the Electrification Challenge: Operational Constraints for Decarbonizing While Growing Demand

Hydroelectricity generating facilities are often associated with multipurpose infrastructure managed through complex governance processes that seek to balance competing priorities for water management. Fundamentally, generating hydroelectricity means allowing water to move out of a particular control structure, which has implications for water users due to spatiotemporal mismatches between water availability and water need. In the US and many other mature electricity systems, building large amounts of new conventional hydroelectricity is unlikely. Simultaneously, though, hydroelectricity is likely to continue to grow in value to decarbonizing grids facing increased demand, which in turn suggests that the balance of priorities for water management at powered dams could shift. Understanding dam governance and how arguments for changing operational regimes at dams to favor hydroelectricity flexibility might be received is thus important for electricity analysts who might wish to know how responsive hydroelectricity might be to changing grid demands. That is, modeling hydroelectricity as fully available subject only to technical electricity-related constraints is inaccurate, but assuming some flexibility—and perhaps more than is currently present in the system—could be reasonable depending on what the competing priorities are.

In the context of electricity modeling, perhaps the two most relevant facts about hydroelectricity governance are that 1) operating frameworks are usually designed to hold for decades, and 2) processes for determining operating frameworks can take years (Benson, 2017; McCann, 2005; Ulibarri, 2015). Changing governance regimes, therefore, is a fairly arduous process. For federal projects, "major" operational changes require congressional review and approval (Benson, 2017), though some changes that might enable hydroelectricity to adapt to the needs of a decarbonizing, growing electricity system might be considered "major" if they do not conflict with other authorized purposes. Notably, however, facilitating grid needs might be less of a priority than it has historically been. Hydroelectricity needs have increasingly been subordinated to competing needs for, e.g., environmental flows and other non-revenue purposes (Benson, 2017). As Ulibarri notes, reducing electricity production or shifting it to less profitable periods is often required for improved environmental outcomes (Ulibarri, 2015). Overall, the implication is that hydroelectricity's value to the grid, both under current conditions and under future conditions that might make it even more valuable, is insufficient to support an assumption that it will be dispatched in the most pro-grid manner. Hydroelectricity is unlike other electricity generation in that it cannot respond to grid needs based on electricity-related signals (financial, technical, or otherwise) alone: other competing priorities represent legal constraints on what hydroelectric facilities can do. Understanding the boundaries of these constraints and their effects on electricity-relevant figures of merit like ramp rate, seasonal capacity factors, and others is the subject of ongoing work.

4. Conclusions

This article argues that better understanding the nonelectricity context of hydroelectricity generating facilities can improve electricity system modeling for decarbonizing and growing electricity systems. Many hydroelectricity facilities are associated with multipurpose dam and reservoir infrastructure whose other priorities imposes particular operational constraints that might be regionally relevant for understanding the role that existing, conventional hydroelectricity capacity can play in the future. This article presents a record linkage between electricity-focused and dam-focused datasets to facilitate analysis of this major renewable electricity system. Initial analysis suggests that nonelectricity purposes associated with hydroelectric facilities vary regionally, with some implications for the kinds of constraints that licenses and other legal regimes related to dam operations might impose. Although hydroelectricity could be extremely valuable to a decarbonized, growing electricity system, recognizing that alternative users of the fuel resource—that is, water—impose restrictions that other power plants generally do not face will be important for accurate understanding of how much hydroelectricity can be expected to facilitate grid changes.

5. References

Avendano, M., Rauss, D., 2019. Southern California Edison’s Blueprint for Integrated Electrification [Viewpoint]. IEEE Electrification Magazine 7, 64–63. https://doi.org/10.1109/MELE.2019.2906633

Bazilian, M., Nussbaumer, P., Rogner, H.-H., Brew-Hammond, A., Foster, V., Pachauri, S., Williams, E., Howells, M., Niyongabo, P., Musaba, L., Gallachóir, B.Ó., Radka, M., Kammen, D.M., 2012. Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. Utilities Policy 20, 1–16. https://doi.org/10.1016/j.jup.2011.11.002

Benson, R.D., 2017. Reviewing Reservoir Operations: Can Federal Water Projects Adapt to Change? Columbia Journal of Environmental Law 42, 73.

Berga, L., 2016. The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. Engineering 2, 313–318. https://doi.org/10.1016/J.ENG.2016.03.004

Boßmann, T., Staffell, I., 2015. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy 90, 1317–1333. https://doi.org/10.1016/j.energy.2015.06.082

BP, 2019. BP Statistical Review of World Energy (No. 68th Edition).

Brown, T.W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., Mathiesen, B.V., 2018. Response to ‘Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems.’ Renewable and Sustainable Energy Reviews 92, 834–847. https://doi.org/10.1016/j.rser.2018.04.113

Bunn, D.W., Seigal, J.P., 1983. Television peaks in electricity demand. Energy Economics 5, 31–36. https://doi.org/10.1016/0140-9883(83)90006-3

Chang, M.K., Eichman, J.D., Mueller, F., Samuelsen, S., 2013. Buffering intermittent renewable power with hydroelectric generation: A case study in California. Applied Energy 112, 1–11. https://doi.org/10.1016/j.apenergy.2013.04.092

Cochran, J., Mai, T., Bazilian, M., 2014. Meta-analysis of high penetration renewable energy scenarios. Renewable and Sustainable Energy Reviews 29, 246–253. https://doi.org/10.1016/j.rser.2013.08.089

Demarty, M., Bastien, J., 2011. GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH4 emission measurements. Energy Policy, Special Section: Renewable energy policy and development 39, 4197–4206. https://doi.org/10.1016/j.enpol.2011.04.033

Denholm, P., Hand, M., 2011. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 39, 1817–1830. https://doi.org/10.1016/j.enpol.2011.01.019

EIA, 2019a. Form EIA-860 detailed data with previous form data (EIA-860A/860B) [WWW Document]. URL https://www.eia.gov/electricity/data/eia860/ (accessed 9.20.19).

EIA, 2019b. Form EIA-923 detailed data with previous form data (EIA-906/920) [WWW Document]. URL https://www.eia.gov/electricity/data/eia923/ (accessed 9.20.19).

FERC, 2013. Present Development of Conventional Hydroelectric Projects [WWW Document]. URL https://www.ferc.gov/industries/hydropower/gen-info/regulation/present-dev.asp (accessed 9.20.19).

François, B., Borga, M., Anquetin, S., Creutin, J.D., Engeland, K., Favre, A.C., Hingray, B., Ramos, M.H., Raynaud, D., Renard, B., Sauquet, E., Sauterleute, J.F., Vidal, J.P., Warland, G., 2014. Integrating hydropower and intermittent climate-related renewable energies: a call for hydrology. Hydrological Processes 28, 5465–5468. https://doi.org/10.1002/hyp.10274

Grubert, E., 2019. Operating US power plants by capacity, age, and fuel [WWW Document]. URL http://emilygrubert.org/wp-content/uploads/2019/02/eia_860_2017_map.html (accessed 9.20.19).

Grubert, E.A., 2016. Water Consumption from Hydroelectricity in the United States. Advances in Water Resources 96, 88–94. https://doi.org/10.1016/j.advwatres.2016.07.004

Hadjerioua, B., Wei, Y., Kao, S.-C., 2012. An Assessment of Energy Potential at Non-Powered Dams in the United States. Oak Ridge National Laboratory.

Holttinen, H., Tuohy, A., Milligan, M., Lannoye, E., Silva, V., Muller, S., Soder, L., 2013. The Flexibility Workout: Managing Variable Resources and Assessing the Need for Power System Modification. IEEE Power and Energy Magazine 11, 53–62. https://doi.org/10.1109/MPE.2013.2278000

Ibanez, E., Magee, T., Clement, M., Brinkman, G., Milligan, M., Zagona, E., 2014. Enhancing hydropower modeling in variable generation integration studies. Energy 74, 518–528. https://doi.org/10.1016/j.energy.2014.07.017

Karier, T., Fazio, J., 2017. How hydropower enhances the capacity value of renewables and energy efficiency. The Electricity Journal 30, 1–5. https://doi.org/10.1016/j.tej.2017.04.014

Levi, P.J., Kurland, S.D., Carbajales-Dale, M., Weyant, J.P., Brandt, A.R., Benson, S.M., 2019. Macro-Energy Systems: Toward a New Discipline. Joule 0. https://doi.org/10.1016/j.joule.2019.07.017

Lovins, A.B., 2017. Reliably integrating variable renewables: Moving grid flexibility resources from models to results. The Electricity Journal 30, 58–63. https://doi.org/10.1016/j.tej.2017.11.006

Marriott, J., Matthews, H.S., Hendrickson, C.T., 2010. Impact of Power Generation Mix on Life Cycle Assessment and Carbon Footprint Greenhouse Gas Results. Journal of Industrial Ecology 14, 919–928. https://doi.org/10.1111/j.1530-9290.2010.00290.x

McCann, C., 2005. Dammed ifYou Do, Damned ifYou Don't: FERC's Tribal Consultation Requirement and the Hydropower Re-licensing at Post Falls Dam. GONZAGA LAW REVIEW 41, 411–458.

Nerini, F.F., Broad, O., Mentis, D., Welsch, M., Bazilian, M., Howells, M., 2016. A cost comparison of technology approaches for improving access to electricity services. Energy 95, 255–265. https://doi.org/10.1016/j.energy.2015.11.068

Northwest Power and Conservation Council, 2019. Grand Coulee Dam: History and purpose [WWW Document]. URL https://www.nwcouncil.org/reports/columbia-river-history/grandcouleehistory (accessed 9.20.19).

Palit, D., Bandyopadhyay, K.R., 2016. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. Renewable and Sustainable Energy Reviews 60, 1505–1515. https://doi.org/10.1016/j.rser.2016.03.034

Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E.G., Luderer, G., 2017. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nature Energy 2, 939. https://doi.org/10.1038/s41560-017-0032-9

Philibert, C., 2019. Direct and indirect electrification of industry and beyond. Oxf Rev Econ Policy 35, 197–217. https://doi.org/10.1093/oxrep/grz006

Pina, A., Silva, C.A., Ferrão, P., 2013. High-resolution modeling framework for planning electricity systems with high penetration of renewables. Applied Energy 112, 215–223. https://doi.org/10.1016/j.apenergy.2013.05.074

Silva Herran, D., Nakata, T., 2012. Design of decentralized energy systems for rural electrification in developing countries considering regional disparity. Applied Energy 91, 130–145. https://doi.org/10.1016/j.apenergy.2011.09.022

Ulibarri, N., 2015. Collaboration in Federal Hydropower Licensing: Impacts on Process, Outputs, and Outcomes. Public Performance & Management Review 38, 578–606. https://doi.org/10.1080/15309576.2015.1031004

US Army Corps of Engineers, 2019. National Inventory of Dams (NID) [WWW Document]. URL https://nid.sec.usace.army.mil/ords/f?p=105:1::::: (accessed 9.20.19).

Yamashita, K., Juan Li, Zhang, P., Liu, C., 2009. Analysis and control of major blackout events, in: 2009 IEEE/PES Power Systems Conference and Exposition. Presented at the 2009 IEEE/PES Power Systems Conference and Exposition, pp. 1–4. https://doi.org/10.1109/PSCE.2009.4840091

Zhang, J., Lei, X., Chen, B., Song, Y., 2019. Analysis of blue water footprint of hydropower considering allocation coefficients for multi-purpose reservoirs. Energy 188, 116086. https://doi.org/10.1016/j.energy.2019.116086

Zhou, T., Voisin, N., Fu, T., 2018. Non-stationary hydropower generation projections constrained by environmental and electricity grid operations over the western United States. Environ. Res. Lett. 13, 074035. https://doi.org/10.1088/1748-9326/aad19f

Declarations of Interest: None.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Vita

Emily Grubert is an Assistant Professor of Civil and Environmental Engineering and, by courtesy, of Public Policy at the Georgia Institute of Technology. Grubert studies how we can make better decisions about large infrastructure systems, with a particular focus on societal priorities and energy and water systems in the US.